



## **Environmentally Adaptive Reverberation Nulling**

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15 April 2006

### **Final Report**

Contract N00014-01-D-0043-D07

For the Period

25 July 2002 – 24 November 2005

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>15 APR 2006</b>		2. REPORT TYPE		3. DATES COVERED	
4. TITLE AND SUBTITLE <b>Environmentally Adaptive Reverberation Nulling</b>				5a. CONTRACT NUMBER <b>N00014-01-D-0043-D07</b>	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>William Hodgkiss; William Kuperman</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Marine Physical Laboratory, Scripps Institution of Oceanography/University of California, San Diego, 291 Rosecrans St., San Diego, CA, 92106</b>				8. PERFORMING ORGANIZATION REPORT NUMBER <b>MPL TM-489</b>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited.</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>This report describes the research performed on behalf of the Office of Naval Research (grant # N00014-01-D-0043 Delivery Order 0007) on the following: The feasibility of enhancing active target detection using environmentally adaptive reverberation nulling techniques has been demonstrated with experimental data and related simulations.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>2</b>	18. NUMBER OF PAGES <b>10</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

# **Environmentally Adaptive Reverberation Nulling**

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## **Abstract**

The feasibility of enhancing active target detection using environmentally adaptive reverberation nulling techniques has been demonstrated with experimental data and related simulations.

## **Research Summary**

A phase conjugate "mirror" time reverses the incident signal precisely returning it to its original source location. This phenomenon occurs independent of the complexity of the medium. The time-reversal process can be accomplished by the implementation of a retransmission procedure. A signal received at an array is time reversed and retransmitted. A full water column source array excited by the phase conjugated (time-reversed) signal received at the array position will focus at the position of the radiating target. The medium fluctuations are embedded in the received signal so that if retransmission can occur on a time scale less than the dominant fluctuations, the medium variability will be eliminated since one back propagates and "undoes" the variability.

Two low frequency (~450 Hz) phase conjugation field experiments were carried out in FY96 and FY97 with the NATO Undersea Research Centre (NURC). These experiments demonstrated that phase conjugation is both feasible and stable at low frequencies in shallow water (~125 m) and that focusing of the retransmitted energy is possible at ranges of at least 30 km. As an outgrowth of these successful experiments, two high frequency (~3.5 kHz) phase conjugation experiments subsequently were carried out with NURC in FY99 and FY00. These experiments demonstrated that high frequency phase conjugation also is feasible with focusing at ranges out to 21 km in both flat (~125 m deep water) and sloping (~125 m deep water shoaling to ~40 m deep water) coastal environments. Furthermore, the use of phase conjugation processing in active target detection was demonstrated in the FY00 experiment where both (artificial) target echo enhancement and reverberation reduction through time reversal focusing were demonstrated. Results from the low and high frequency experiments are presented in [1-4,6,8-10].

In the same manner in which a probe source facilitates focusing acoustic energy at a specific range/depth cell, it also enables steering a null [5,7]. Furthermore, an adaptive null-steering approach is suggested which does not require a probe source at all. An eigenvalue/eigenvector decomposition of the reverberation signal from a range of interest

yields the replica vectors between the source and scatterers where the reverberation is generated. Subsequent transmissions from the source/receive array (time-reversal mirror) weighted by the non-dominant eigenvectors minimizes the acoustic field interacting with the boundaries. Thus, this active null-steering method provides an approach for mitigating high levels of boundary reverberation without requiring a probe source while at the same time facilitating weak target detection. The theory of active reverberation nulling is discussed in [11]. In addition to active reverberation nulling, a passive (receive only) approach also has been developed. In this case, the dominant reverberation eigenvector at each range is used to project out of the receive array data that component of the acoustic field dominated by scattering from the boundaries. Thus, a range-evolving null-steering approach is implemented for processing the received data from conventional active transmissions.

Two recent Focused Acoustic Fields (FAF) experiments were carried out with NURC in FY03 and FY04. The FAF-03 experiment took place in March-April 2003 north of Elba Island, Italy. In addition to carrying out time reversal focusing at 3.5 kHz in Winter/Spring sound speed profiles, the 29-element source/receive array hardware was modified to enable operation at 850 Hz. Analysis of the active reverberation nulling data collected in FAF-03 appears in [12]. The FAF-04 experiment was carried out in July 2004 north and south of Elba Island, Italy. During part of this experiment, the 29-element, 3.5 kHz source/receive array was reconfigured and operated successfully as a billboard array. In addition to demonstrating conventional beam steering in the horizontal, modest vertical aperture reverberation focusing and nulling also were shown feasible [13].

### Examples of Research Results

The environmentally adaptive reverberation nulling concept is illustrated in Fig. 1. Shown is the source, target, and boundary backscattering geometry. With a single source (or small-aperture conventional active system), boundary reverberation severely limits weak target detection. The time-reversal mirror (TRM) steers an ensonification null on the boundaries at a range of interest thus enhancing the target echo-to-reverberation ratio.

Discussed in [11], the reverberation nulling process is implemented by forming the array covariance matrix from a range window of the reverberation time series. For this initial step, the transmit beam is conventional (e.g. a broadside beam) and used to obtain an example of boundary reverberation for this waveguide and array geometry. An eigenvalue/eigenvector decomposition of the array covariance matrix identifies the replica vectors corresponding to the strong boundary backscatter. A majority of the reverberation energy typically is captured in the first few eigenvalues. The corresponding eigenvectors steer towards the major sources of backscatter. Subsequent transmissions from the TRM weighted by the non-dominant eigenvectors minimizes the acoustic field interacting with the boundaries at the range of interest.

Large-aperture (78 m) TRM data were collected during the FAF-03 experiment carried out with NURC in March-April 2003 in 105 m water north of Elba Island, Italy. Fig. 2 illustrates reverberation nulling results at 3.5 kHz with 100 ms CW pings. A consistent clutter feature is evident in the backscatter from a range of 2.5 km and can be associated with a bathymetric

feature SE of the source/receive array (SRA). Through the active reverberation nulling process, the backscatter from this feature is removed reducing the reverberation level from this range by 3 dB.

A modest vertical aperture (8.4 m), billboard source/receive array was deployed during the second half of the FAF-04 experiment carried out with NURC in July 2004 in 50 m water south of Elba Island, Italy. Fig. 3 illustrates active reverberation nulling results at 3.5 kHz with 100 ms CW pings. A clutter feature is evident in the backscatter from a range of 2.5 sec (two-way travel time). Through the active reverberation nulling process, the backscatter from this range is reduced by approximately 4 dB based on a simple incoherent average across the billboard array elements.

Data from the first half of FAF-04 will be used to illustrate the passive environmentally adaptive reverberation nulling concept. An echo repeater (artificial target) was deployed to 70 m depth from the *Alliance* in 121.5 m deep water at a range of approximately 3 km from the bottom-moored 78 m - aperture source/receive array. Transmissions were generated every 15 sec with the echo repeater responding to every other ping. Fig. 4 shows the observed downward-refracting sound speed profile and a full water column transmission loss (TL) prediction assuming a conventional broadside transmission at 3.5 kHz from the source/receive array. Substantial energy from the transmission interacts with the seafloor in the vicinity of 1.5 and 3.0 km.

Fig. 5 shows an example of the received reverberation (echo repeater absent) on all elements of the source/receive array for a single broadside 100 ms CW transmission. Similar to the procedure discussed in [11], the passive reverberation nulling process is implemented by first estimating a sequence of narrowband array covariance matrices at successive range intervals by averaging over 8 pings. Also shown in Fig. 5 is a plot of the first three eigenvalues vs. time of these reverberation-only covariance matrices. The first eigenvalue dominates the others by 5-10 dB and exhibits significant variability with time (range) including large levels related to major bottom interactions. The corresponding sequence of eigenvectors steer towards the major sources of backscatter.

A simple incoherent average across the array elements will be used as an unnormalized target detection test statistic. Fig. 6 shows the resulting power time series without reverberation nulling for 8 pings with the echo repeater absent and present. The solid blue line is the average of all reverberation-only results and could be used to normalize the test statistic. The vertical line just before 4 sec is the range of the target echo. Similarly, Fig. 7 shows the results after using a projection operation to remove that component of the data in the direction of the dominant reverberation-only eigenvector. The detectability of the echo repeater is enhanced by the passive reverberation nulling process.

## Acknowledgments

This project was a joint effort between MPL and the NATO Undersea Research Centre (NURC). The FAF-03 and FAF-04 experiments were co-sponsored by ONR Code 321US project "Offboard Active Surveillance and Communications" (Contract N00014-01-D-0043-D06).

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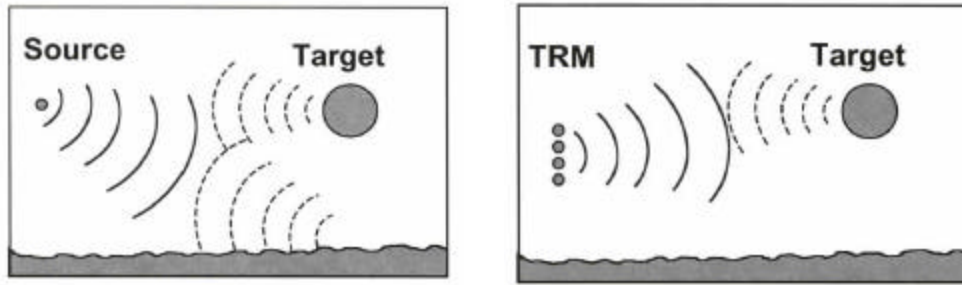


Figure 1. Target and boundary (surface and bottom) backscatter. (a) Single source (or small-aperture conventional active system). (b) Time-reversal mirror (TRM) reducing ensonification of the boundaries in the vicinity of the target range.

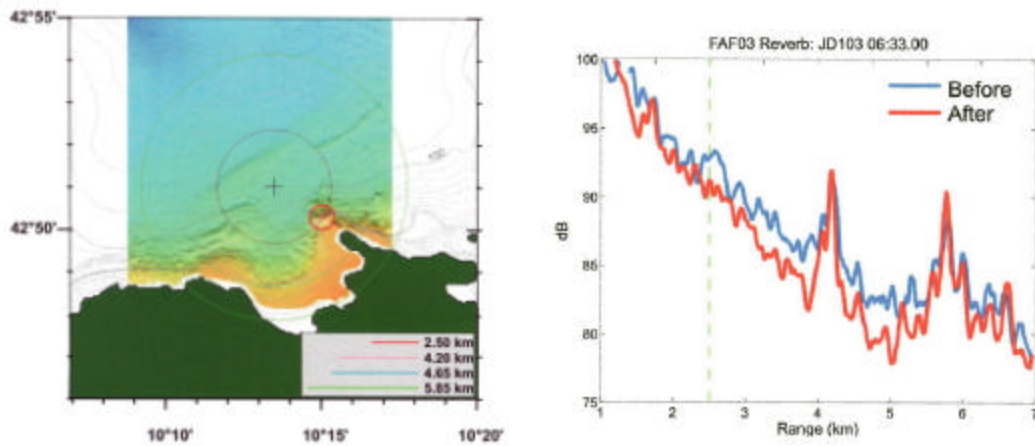
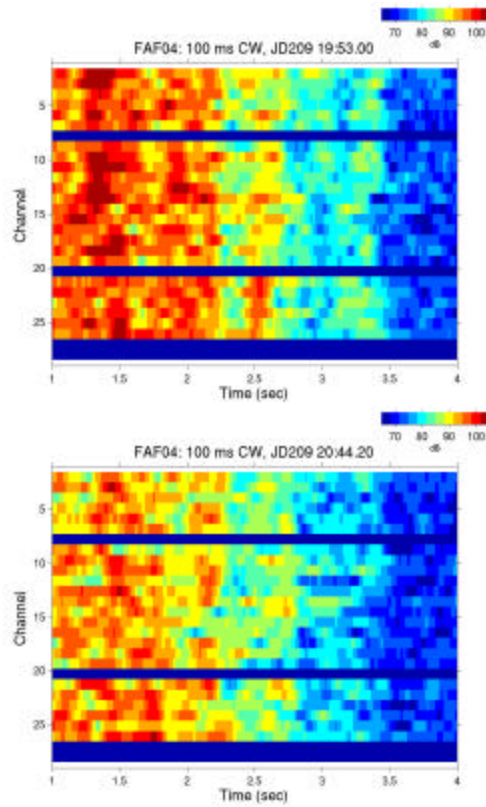
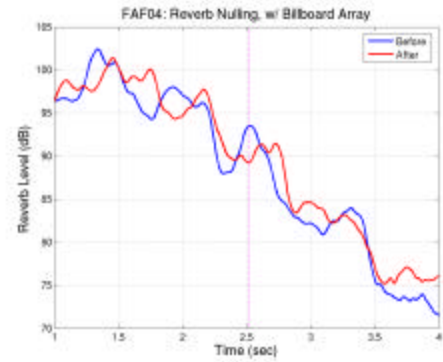


Figure 2. Reverberation nulling example from FAF-03 at 3.5 kHz. (a) Bathymetric feature 2.5 km SE of the SRA likely responsible for the clutter peak evident in the data. (b) Reverberation time series observed by the SRA (incoherent average of all SRA elements) showing the results before and after implementing the active reverberation nulling process. The clutter feature at 2.5 km range is removed reducing the reverberation level from this range by 3 dB.



## Broadside Transmission



## Incoherent Average

## Null Transmission

Figure 3. Reverberation nulling example from FAF-04 at 3.5 kHz with 100 ms CW pings. (a) A clutter feature is evident in the element-level reverberation return from a broadside transmission at 2.5 sec (upper-left panel). (b) The backscatter from this range is reduced significantly when using a null transmission (lower-left panel). (c) A simple incoherent average across the billboard array elements shows a reduction in reverberation level by approximately 4 dB at this range (right-panel).

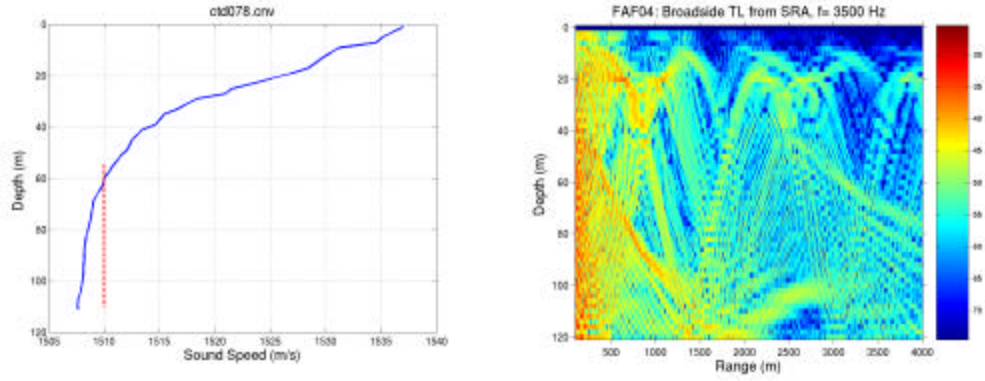


Figure 4. FAF-04 environmental characteristics. (a) Observed downward-refracting sound speed profile with the lower 20 elements of the source/receive array indicated. (b) Full water column transmission loss (TL) prediction assuming a conventional broadside transmission at 3.5 kHz from the source/receive array.

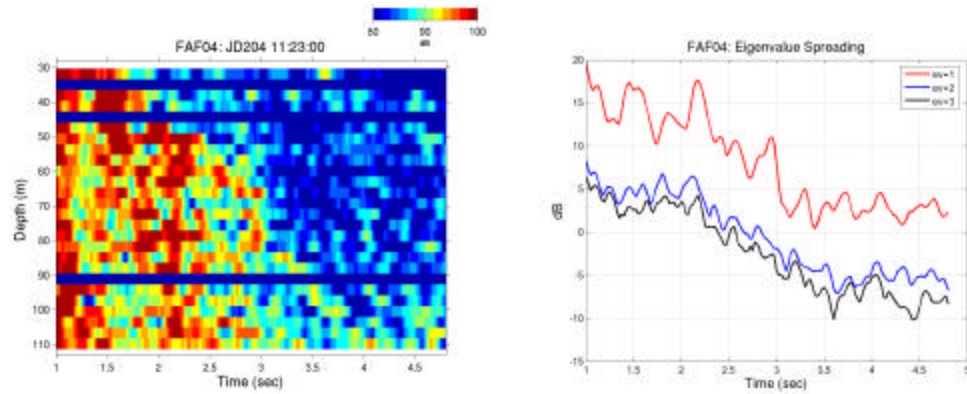


Figure 5. FAF-04 reverberation. (a) Observed reverberation from a single broadside 100 ms CW transmission at 3.5 kHz. (b) First three eigenvalues vs. time (range) of the sequence of reverberation-only covariance matrices.

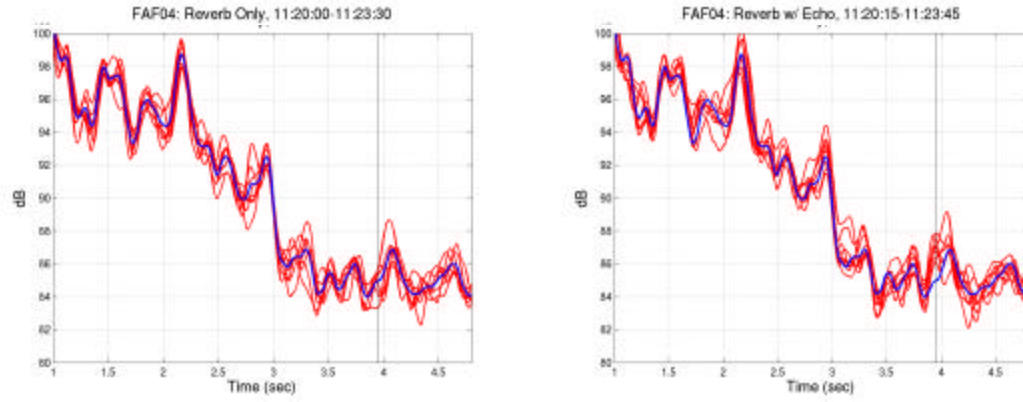


Figure 6. Echo repeater detection without reverberation nulling (8 pings). (a) Echo repeater absent (solid blue line is the average of all reverberation-only results). (b) Echo repeater present (vertical line just before 4 sec is the range of the artificial target echo).

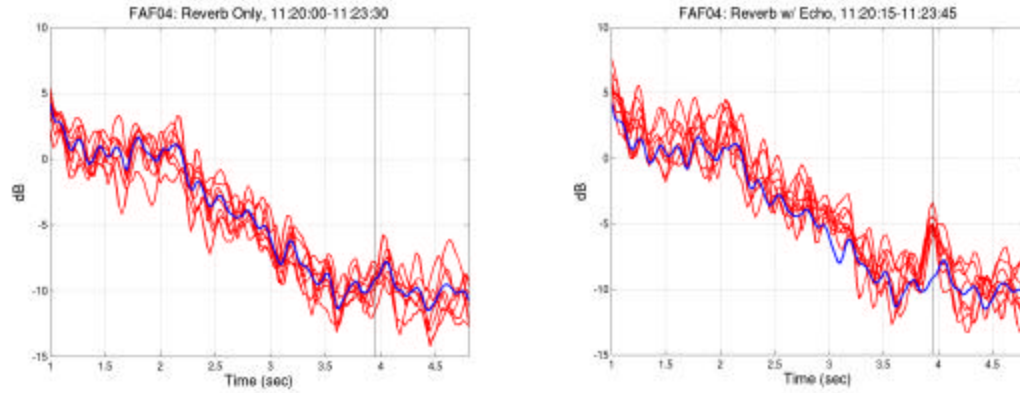


Figure 7. Echo repeater detection with passive reverberation nulling (8 pings). (a) Echo repeater absent (solid blue line is the average of all reverberation-only results). (b) Echo repeater present (vertical line just before 4 sec is the range of the artificial target echo).